THE OTHER NUCLEAR REACTION

Neutron-capture reactions, responsible for the creation of most chemical elements, are being studied in detail for nuclear physics, nuclear technology, and national security.

It's not fission or fusion. It's not alpha, beta, or gamma decay, nor any other nuclear reaction normally discussed in an introductory physics textbook. Yet it is responsible for the existence of more than two thirds of the elements on the periodic table and is virtually ubiquitous anywhere nuclear reactions are taking place—in nuclear reactors, nuclear bombs, stellar cores, and supernova explosions.

It's neutron capture, in which a neutron merges with an atomic nucleus. And at first blush, it may even sound deserving of its relative obscurity, since neutrons are electrically neutral. For example, add a neutron to carbon's most common isotope, carbon-12, and you just get carbon-13. It's slightly heavier than carbon-12, but in terms of how it looks and behaves, the two are essentially identical. Add another neutron, however, and the story starts to get more interesting. Carbon-14 is radioactive with a 6000-year half-life. Carbon-15 and -16 are even more radioactive, decaying in mere seconds. Los Alamos nuclear scientist Shea Mosby, whose research is currently redefining human knowledge of key neutron-capture reactions, got his start doing graduate work on zeptosecond-lived carbon-*21* (that's a billionth of a trillionth of a second).

"Nuclear power, nuclear weapons, nuclear medicine, and nuclear diagnostics—these things help to carry humanity forward, and neutron-induced reactions are vitally important to all of them," says Mosby. "So we strive to measure precise parameters for neutron capture by many different isotopes as part of the broader effort to understand all the ways to create and destroy every isotope of every element. And in nearly every isotope we've tested so far, we discovered something new and valuable."

DANCE at LANSCE

At 30, Mosby is young for a Los Alamos staff scientist. His carbon-isotope research caught the attention of Lab scientist and now-colleague Aaron Couture during a recruiting trip to Mosby's graduate school. Couture hired Mosby as a postdoctoral researcher, broadening Mosby's experience with neutron capture to heavier elements, from iron to plutonium. Two years and 15 journal articles later, Mosby was given a permanent position.

Mosby's office and lab are located within the Los Alamos Neutron Science Center (LANSCE) complex, a proton accelerator facility that can be used to generate neutrons, which are siphoned off for his neutron-capture experiments. He wears a dosimeter around his neck to track his exposure to radiation in the lab. And when he's not in the lab, he can keep tabs on his various experiments simultaneously from his office computer with not one or two but *five* widescreen monitors—displaying graphs and computer codes without a single pixel of unused space. Data printouts pinned to the wall on the left side of the office and techno-scribble densely covering the whiteboard on the right side testify to a man on a mission: developing, or at least contributing to, a detailed understanding of complex atomic nuclei. For that, he'll need to collect and tabulate a lot of cold, hard data.

Mosby's primary experimental apparatus for doing this is the Detector for Advanced Neutron Capture Experiments (DANCE), a heavily instrumented metal sphere with neutrons piped through the center, where they interact with a sample of the isotope being studied. Whenever neutrons enter the sample nuclei, they produce an excited nuclear state—essentially a high-energy arrangement of the protons and neutrons moving around in the nucleus. That high-energy state is unstable and proceeds to "relax" to the isotope's ground state, shedding its excess energy by emitting a series of gamma-ray photons. Those gamma rays enter a barium-fluoride scintillator array, where they kick electrons up to high speeds, energizing the material's crystal structure. The crystal then relaxes to its ground state by emitting ultraviolet photons, which are picked up by high-end optical detectors called photomultiplier tubes (PMTs), resulting in a measurable electrical signal. The scintillator array surrounds the sample, and the PMTs—which are extremely sensitive to ultraviolet but not to gamma rays—surround the scintillator array.

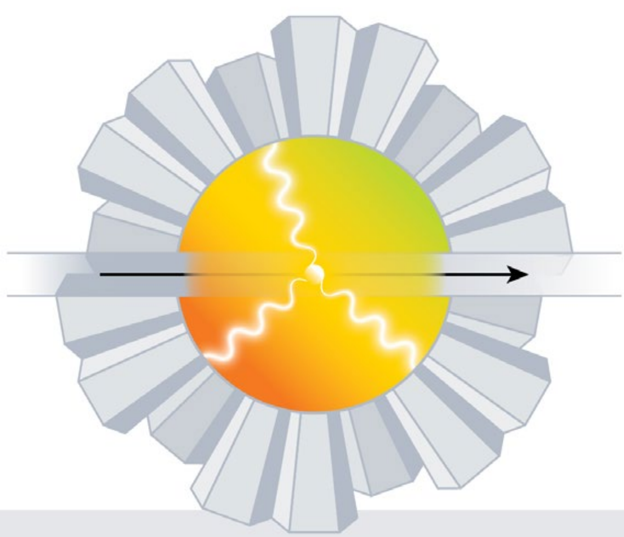
Once an experiment has been carried out, Mosby has to perform some calculations to obtain from DANCE's measurements a quantity known as the neutron-capture cross section—the proclivity for neutron capture of the type he measures to occur. From a practical standpoint, this single number encapsulates all useful information about that neutron capture by a given isotope. It is needed to understand and predict, for example, the mix of nuclear reactions that will take place inside a nuclear reactor, a weapon, or a star. It allows scientists to calculate the rate at which neutrons are lost to the reaction and the corresponding rate at which the resulting neutron-enriched nuclei do whatever they do next—whether that may be nuclear fission, radioactive decay, or capturing another neutron.

For example, in a typical nuclear power plant, neutrons bombard uranium-235 fuel. Several things can happen next. Ideally, the neutron induces a uranium atom to fission, splitting it in two and, in the process, spitting out a few more neutrons to interact with other uranium nuclei. Alternatively, the original neutron might enter the nucleus in such a way as to cause another neutron, or more than one, to reemerge. Or the neutron might be captured by the nucleus and excite (energize) it, causing a sequence of gamma rays to emerge. All of these processes have their own cross sections and affect the composition of the remaining neutron-and-fuel mixture and therefore the performance of the reactor. Different instruments measure the different cross sections for these processes; DANCE does its part by measuring the cross section for neutron capture leading to the emission of gamma rays.

U and Pu

Before Mosby came to work at Los Alamos, some of his soon-to-be colleagues had set out to measure the neutron-capture cross section for uranium-235 and uranium-238, largely as a matter of course, to see if they could improve accuracy over previous measurements made with less sophisticated equipment. They did that, but interestingly, they also discovered something new based on DANCE's unique ability to resolve the many gamma rays involved in the nucleus's post-capture relaxation process.

It turned out that all prior calculations of the cross section as a function of neutron energy were greatly flawed: they predicted a spectrum of gamma rays very different from what DANCE observed. The Laboratory's John Ullmann and others tracked down the discrepancy to a previously unknown set of transitions between nuclear states. Before this discovery, the calculated cross sections often differed from measurements by a factor of two at least—sometimes as much as ten! Now they're off by only 10 *percent*. With measurements this complex, that's a remarkable achievement. And because not all isotopes can be readily measured (some decay too quickly, others too violently), it is critically important to be able to reliably calculate the ones that can.



Neutrons pass through the DANCE detector and interact with an isotope sample at the center. Those neutrons that undergo neutron capture, entering a nucleus of the sample material, cause that nucleus to transition to a high-energy, excited state. The nucleus relaxes to its ground state by rapidly transitioning through a series of lower-energy states, emitting a gamma ray with each transition. Scintillators and detectors surrounding the sample obtain the energy and intensity of each gamma ray emitted.

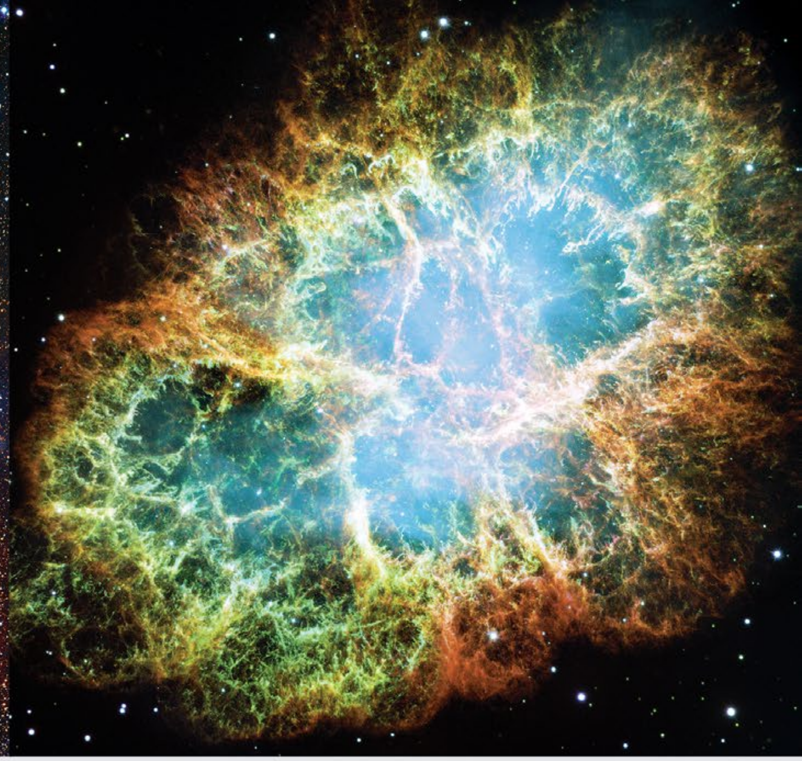
Mosby subsequently set out to measure the cross section for neutron capture onto plutonium-239, the primary fuel in a modern nuclear weapon. His results helped to resolve disputed cross-section estimates at the upper end of the relevant neutron-energy range. These results have been incorporated into the U.S. standard "evaluated nuclear data file" published by the National Nuclear Data Center (NNDC). This file is an important repository of nuclear data for use in a wide variety of nuclear technology applications.

According to Mosby, such updates are particularly important because some older NNDC data—particularly from the 1950s to 70s heyday of nuclear science and technology—suffers from inaccuracies caused by underestimated systemic uncertainties in the measurements made at the time. This can set back the field, delaying acceptance of updated values when new cross-section measurements are outside of the published uncertainty range because that range wasn't big enough to begin with, as was the case with the new plutonium-239 measurement at DANCE.

"It reminds me of the old saying, 'you have to be first, or right,'" says Mosby. "We're certainly in the business of doing it right, and we can't rely on earlier measurements for confirmation because those experimenters didn't have the decades of experience we have now. They didn't know all the things that can go wrong with a measurement like this, all the little gotchas. That means, for us, there is no answer key. We're writing the answer key."

In terms of Los Alamos's national security mission, getting that answer key right has two especially important uses. First, it is relevant for stockpile stewardship: maintaining the nation's nuclear deterrent largely with mathematical analysis instead of full-blown nuclear testing. That much reliance on calculations demands that all the input parameters be correct, including cross sections and a weapon's initial isotopic abundances. Fortunately, when it comes to maintaining the nation's own weapons, those initial abundances are known.

Second, the Lab is a specialist in nuclear diagnostics: analyzing a radioactive sample (such as the debris from a nuclear detonation) to reconstruct the details of how it was produced (the nature of the weapon and its nuclear material). In principle, this can be done by comparing the abundances of different isotopes present in the sample to determine what must have changed when the bomb went off. That only works if scientists have some way of knowing the initial abundances of certain isotopes (zero, for example, for isotopes produced solely by the weapon) and all the cross sections for



When a star reaches old age, it swells to become a red giant; several are visible in this image of open star cluster NGC 3532. Some aging red giants, also known as asymptotic giants, host a number of neutron-producing reactions and, over time, produce heavier elements by successive neutron capture onto nuclei.

CREDIT: (Left) ESO/G. Beccari; (Right) NASA, ESA, J. Hester, A. Loll (ASU)

Massive stars, more than about ten times the mass of the sun, produce copious neutrons just before they go supernova, as do collisions between neutron stars, which are often left behind after such supernovae. Either event leads to an explosion that mashes nuclei and neutrons together, rapidly producing heavier elements by neutron capture. Shown here, the Crab Nebula, which harbors a neutron star near its center, is a supernova remnant.

every reaction that creates and destroys isotopes during the detonation. The more accurate the cross-section measurements are, the more sensitive the diagnostics will be.

Dying stars

Mosby's answer key isn't only for bombs, power plants, and specialized nuclear physics labs. It's also integral to understanding the universe because neutron-capture reactions take place naturally in many astrophysical settings. These reactions are not only a point of academic interest to astronomers; they are also fundamental to the origin of most elements on Earth, including many that are important to industry (e.g., precious metals and medical isotopes) and a handful that are required for the human body to function (e.g., molybdenum in metabolic enzymes and iodine in thyroid hormones). Neutron-capture reactions are the primary source for most of these elements. As Mosby puts it, "Neutron-capture reactions underwrite our very existence."

For instance, stars generate much of their energy from a variety of nuclear-fusion reactions, which merge smaller elements into bigger ones and produce most of the first 30 or so elements on the periodic table—elements like oxygen, silicon, and iron. (Hydrogen and helium are notable exceptions, having formed in abundance in the big bang.) But when stars reach old age, those fusion reactions become more complicated, with some producing free neutrons that are periodically captured by different nuclei present in the star. If the resulting nuclei are too neutron-rich to be stable, they will undergo beta decay, with a neutron turning into a proton (plus some other lighter particles), thus advancing the element by one position on the periodic table. (Elements are defined by atomic number, the number of protons in the nucleus.) Another neutron can then be added, followed by another beta decay, thereby creating additional elements and moving across the periodic table. This is known as the slow, or s-process, one of two main varieties of astrophysical neutron capture.

THE GOLD IN MY WEDDING BAND PROVES THERE ARE NEUTRON-CAPTURE REACTIONS IN THE UNIVERSE

The other occurs when massive stars die via supernova explosions or when neutron stars, frequent relics of such supernovae, collide with one another. Either event involves a blast of nuclei and neutrons, spawning a flurry of neutron-capture reactions known as the rapid, or r-process. The rapid, explosive addition of neutrons generally doesn't leave enough time for beta decays to occur; as a result, many neutrons are crammed into each nucleus before there is a sufficient pause for a beta decay or two. Then more neutrons are slammed in before another beta decay occurs, and so on. Due to the neutron excess, r-process elements are highly radioactive, and only after the neutron infusion abates does a series of beta decays bring r-process elements back toward stability.

The s-process can produce elements up to bismuth, with atomic number 83; the r-process reaches uranium (92) and beyond. The r-process occurs in nuclear-weapon detonations as well. In fact, the last two elements that can be produced by the r-process, einsteinium (99) and fermium (100), were first discovered in the debris from the original hydrogen bomb detonation in 1952. Most heavy elements can be produced by both processes. Says Mosby, "The gold in my wedding band is proof of these neutron-capture reactions in the universe."

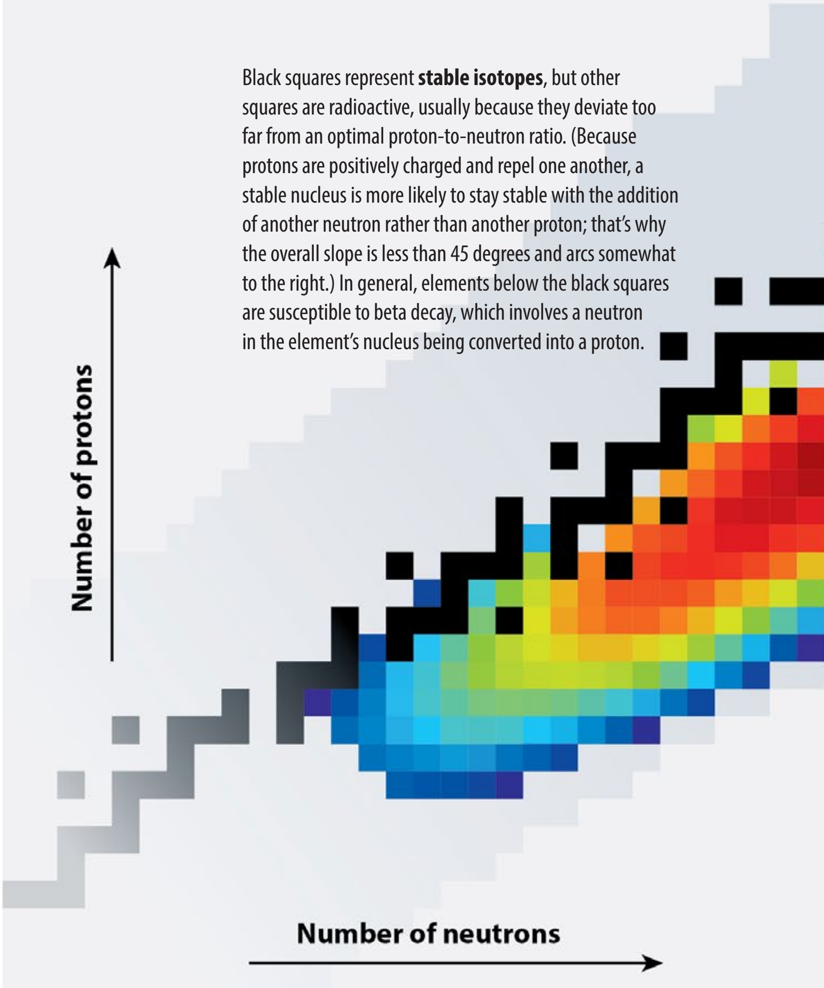
Astrophysicists want to know how much of each element can be produced in each way in order to describe the chemical evolution of the universe. Mosby and colleagues have already experimented on some key branch points in the s- and r-processes. For example, they have discovered salient details in the process of neutron capture onto nickel-63. Nickel-63 beta decays to copper-63, which can capture another neutron and then beta decay to zinc-64. But DANCE results show that the cross section for neutron capture onto nickel-63 is substantially higher than previously thought, making it more likely to go to nickel-64 before decaying and therefore significantly reducing the production of copper-63 and zinc-64. Similarly, a DANCE study in collaboration with Louisiana State University updated neutron-capture cross sections for zinc-66, -67, and -68, which govern the likelihood of producing s-process isotopes up to rubidium, seven elements beyond zinc on the periodic table. Going forward, astrophysical models of element synthesis have to be modified to take these results into account.

"I feel lucky," says Mosby, "to be able to do research to advance nuclear technology and, at the same time, discover key details about how the universe works."

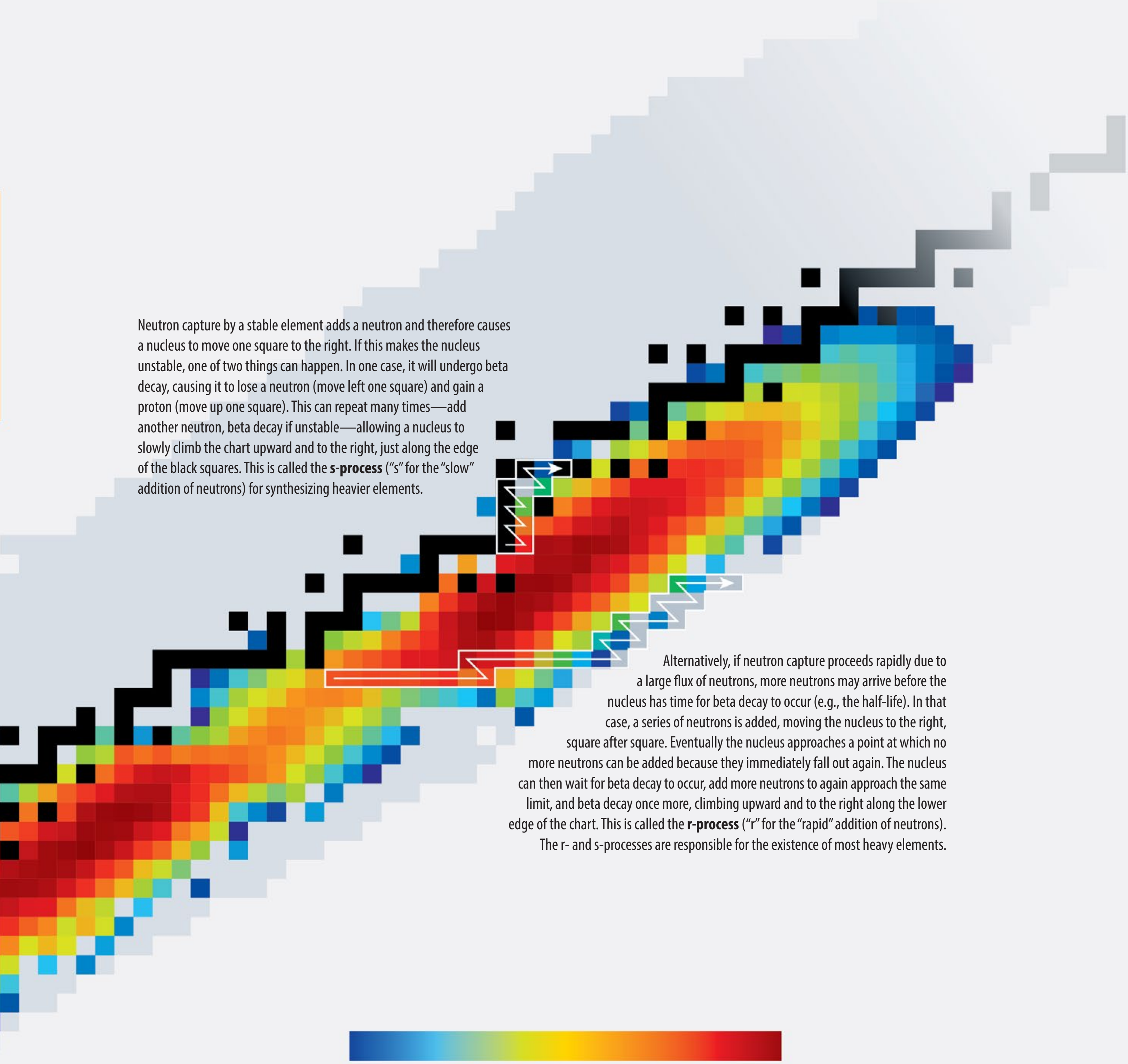
The problem with prediction

DANCE is a highly sophisticated and successful experimental-physics machine. And yet, at its heart, it exists almost entirely for the purpose of covering up a hole in humanity's ability to do nuclear physics: the ability to express the mathematical form of the strong nuclear force as it applies to all but the simplest nuclei. Physicists have well-established equations for the electromagnetic and gravitational forces, but they can't perform an exact calculation to describe the force that confines protons and neutrons in an atomic nucleus (overpowering the repulsive electrical force among positively charged protons). As a result, physicists can't predict from first principles the behavior, including interaction cross sections, for complex nuclei. Instead, they must measure these cross sections where possible and use the results to help estimate the properties of nuclei that have not been, or cannot be, measured.

The chart of the nuclides, a section of which is shown here, is the nuclear-physics equivalent of chemistry's periodic table. The vertical axis counts the number of protons in a nucleus (which determines the element), and the horizontal axis counts the number of neutrons (which determines the isotope of that element). Each square on the chart represents a particular isotope of a particular element.



Black squares represent **stable isotopes**, but other squares are radioactive, usually because they deviate too far from an optimal proton-to-neutron ratio. (Because protons are positively charged and repel one another, a stable nucleus is more likely to stay stable with the addition of another neutron rather than another proton; that's why the overall slope is less than 45 degrees and arcs somewhat to the right.) In general, elements below the black squares are susceptible to beta decay, which involves a neutron in the element's nucleus being converted into a proton.



Neutron capture by a stable element adds a neutron and therefore causes a nucleus to move one square to the right. If this makes the nucleus unstable, one of two things can happen. In one case, it will undergo beta decay, causing it to lose a neutron (move left one square) and gain a proton (move up one square). This can repeat many times—add another neutron, beta decay if unstable—allowing a nucleus to slowly climb the chart upward and to the right, just along the edge of the black squares. This is called the **s-process** ("s" for the "slow" addition of neutrons) for synthesizing heavier elements.

Alternatively, if neutron capture proceeds rapidly due to a large flux of neutrons, more neutrons may arrive before the nucleus has time for beta decay to occur (e.g., the half-life). In that case, a series of neutrons is added, moving the nucleus to the right, square after square. Eventually the nucleus approaches a point at which no more neutrons can be added because they immediately fall out again. The nucleus can then wait for beta decay to occur, add more neutrons to again approach the same limit, and beta decay once more, climbing upward and to the right along the lower edge of the chart. This is called the **r-process** ("r" for the "rapid" addition of neutrons). The r- and s-processes are responsible for the existence of most heavy elements.

Another key nuclear process, **fission**, involves the splitting of heavy nuclei, such as uranium-235 or plutonium-239, into two smaller nuclei, plus a few excess neutrons. Neutron-capture prior to fission can affect how well the fission reactions proceed, what smaller nuclei get produced, and in what quantities. Such information can be used, for example, in nuclear diagnostics, wherein one infers properties of a nuclear weapon by the isotopic makeup of its debris. Shown here, heat-map coloring indicates the likelihood that a particular isotope emerges from fission of plutonium-239.

The DANCE neutron-capture experiment.
CREDIT: Robb Kramer/LANL

Even the act of comparing measurements to theory is frustratingly inexact. Mosby seeks to measure the cross section for neutron capture resulting in the emission of gamma rays. But what he actually measures is the distribution of emitted

I GET TO ADVANCE NUCLEAR TECHNOLOGY AND DISCOVER KEY DETAILS ABOUT HOW THE UNIVERSE WORKS

gamma rays after neutron capture, which theoretically depends on the particular nuclear structure of the isotope being investigated. In order for his measurements to translate into the ability to predict other isotopes' cross sections, he must develop a reliable mathematical relationship that links the isotope's nuclear structure, its gamma-ray emissions following neutron capture, and its cross section.

Unfortunately, for most isotopes, the gamma-ray emissions are far too complicated to be predicted mathematically. When a neutron is absorbed, it deforms the nucleus somewhat, sending that nucleus into the highly excited state that relaxes by emitting gamma rays. But there can be thousands of intermediate states between this excited state and the ground state, meaning that thousands of gamma rays of different energies are emitted along the way. It's too computationally intensive to calculate directly. So instead, Mosby, like others in the field, is forced to work with an approximation, a complicated average across all the gamma-ray energies known as the photon strength function (PSF). It's not ideal, but it's the best he can do. He uses DANCE measurements of gamma rays to calibrate estimated PSFs, and works in two directions from there. In the theoretical direction, he uses gamma-ray measurements to reveal the properties of the isotope's intrinsic nuclear structure. And in the practical direction, he uses an established formula—albeit a messy one—to arrive at the cross section needed for nuclear science and technology applications.

Not all isotopes are created equal for this kind of work. Mosby recently tried an experimental series on the isotope zirconium-96 because it happens to have an unusually small number of nuclear transitions—at least compared to actinide elements like uranium and plutonium that DANCE often studied in the past—between its ground state and the various states excited by neutron capture. Here, the averaging built into the PSF starts to break down because there aren't enough different gamma-ray producing transitions to develop a meaningful average. In one sense, that makes zirconium-96 a particularly clean isotope for study, in that it might allow a simpler-than-usual connection between nuclear structure, neutron-induced deformation of the nucleus, the PSF, and the cross section. The results may help identify and correct the flaws in neutron-capture cross sections across the board.

For Mosby's part, he is interested in a holistic treatment of the problem, pushing the limits of the PSF—an artificial construct—to get at the underlying reality of the available nuclear states. Measure some isotopes. Learn to calculate others. Work backwards to better understand nuclear physics, and tabulate cross sections for nuclear power, medicine, weapons, diagnostics, astrophysics, and other applications yet to be discovered. Along the way, he savors being able to make tangible progress every time he throws a neutron at a new isotope. LDRD

—Craig Tyler

More **nuclear physics applications** at Los Alamos

- **Nuclear fusion power research**
  http://www.lanl.gov/discover/publications/1663/2016-july/small-fusion-could-be-huge.php
- **Subcritical nuclear weapons experiments**
  http://www.lanl.gov/discover/publications/1663/2014-august/critical-subcritical.php
- **Nuclear medicine**
  http://www.lanl.gov/discover/publications/1663/2016-march/nuclear-war-against-cancer.php
- **Nuclear astrophysics**
  http://www.lanl.gov/discover/news-release-archive/2016/April/04.21-burst-code-probes%20.php
  (See also page 2 of this issue of *1663*.)
- **Entombing nuclear waste**
  http://www.lanl.gov/discover/publications/1663/2013-march/disposing-nuclear-waste-in-salt-bed%20.php

More@LANL